Recent Lattice QCD results and implications for BES

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Bielefeld-BNL-CCNU collaboration

A. Bazavov, H.-T. Ding, P. Hegde, O. Kaczmarek, F. Karsch, E. Laermann, S. Mukherjee, H. Ohno, P. Petreczky, C. Schmidt, S. Sharma, W. Soeldner, P. Steinbrecher, M. Wagner

Outline

1. The QCD phase diagram: outstanding issues from lattice
2. Equation of state at finite μ_B
3. Freezeout and Lattice observables

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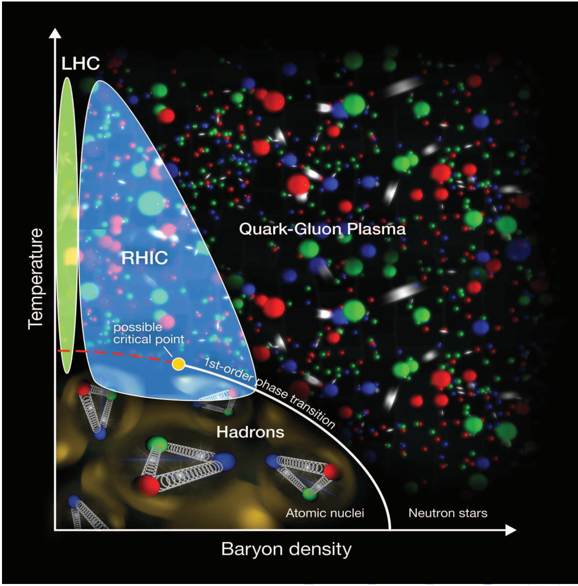

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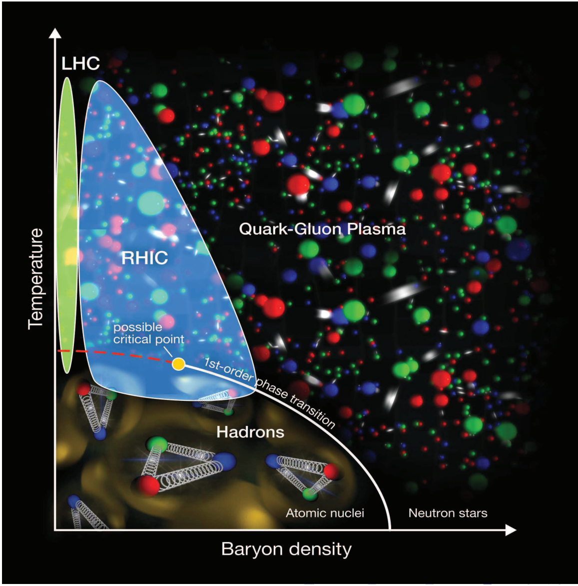

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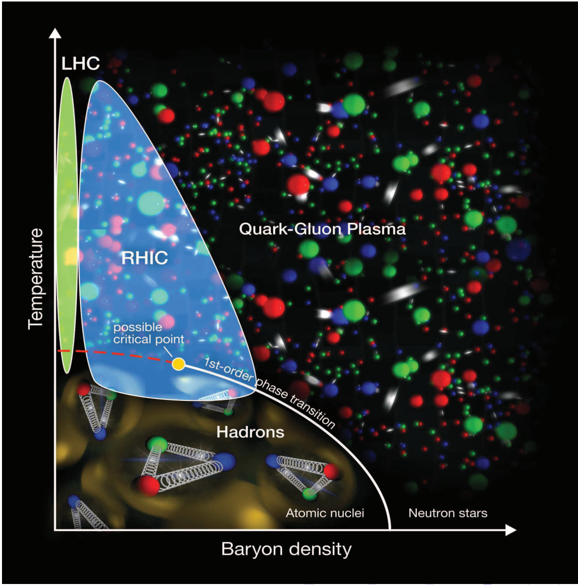

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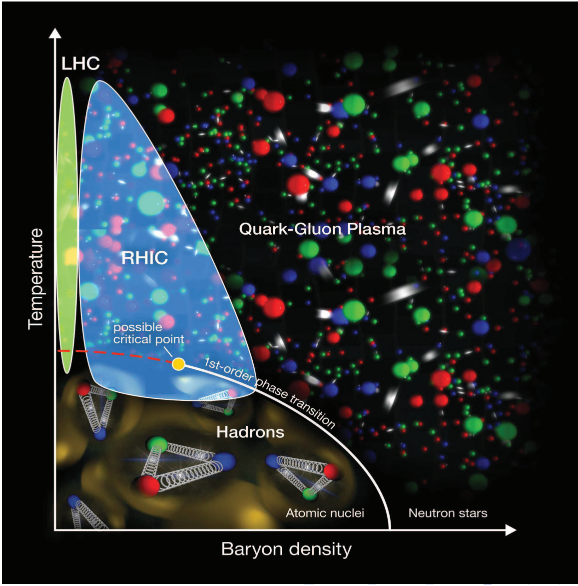

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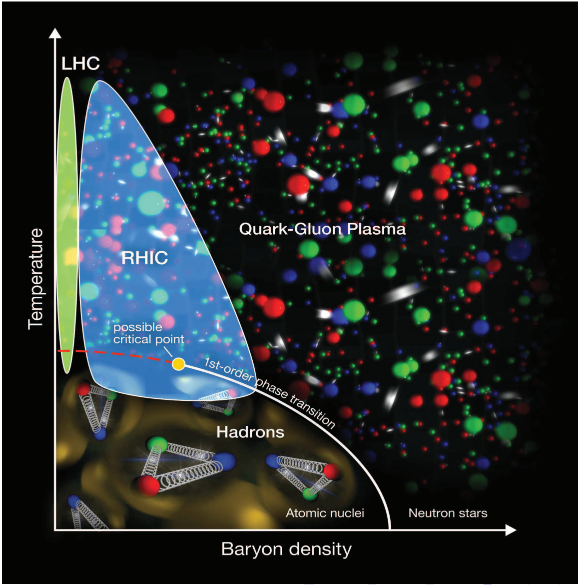
- Bracket the position of CEP in phase diagram.
- Understand the critical behavior due to the light quarks in the crossover region.



Basic observables

- One of the methods to circumvent sign problem at finite μ: Taylor expansion of physical observables around $\mu = 0$ in powers of μ/T.

$$\frac{P(\mu_B, T)}{T^4} = \frac{P(0, T)}{T^4} + \frac{1}{2}\left(\frac{\mu_B}{T}\right)^2 \chi_2^B(0, T) + \frac{1}{4!}\left(\frac{\mu_B}{T}\right)^4 \chi_4^B(0) + \ldots$$

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- These observables imp. for EoS $\rightarrow \chi_6^B$ can already constrain QCD pressure in the regime approximated by Hadron Resonance gas model.

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  - Matrix inversions increasing with the order
  - Delicate cancellation between a large number of terms for higher order QNS.

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- Efficient codes based on modern computer architectures are being developed. [O. Kaczmarek, C. Schmidt, P. Steinbrecher, M. Wagner, 14]

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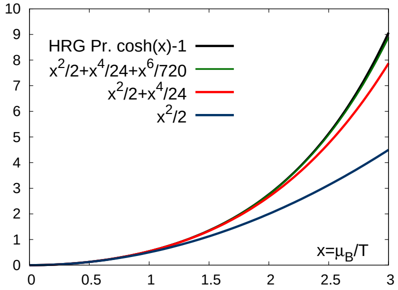

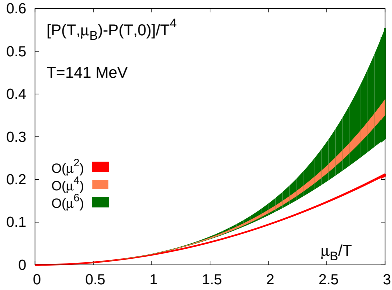

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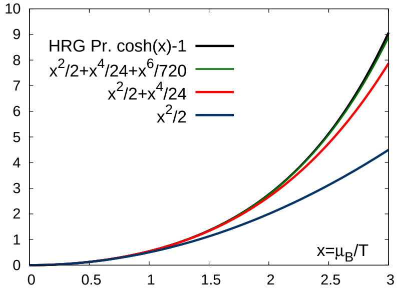
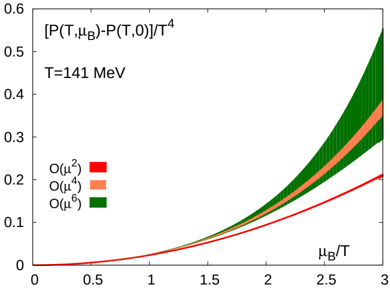
- We are improving the errors on χ_6^B $\rightarrow$ increase statistics twofold this year.





EoS away from criticality

- The pressure for $T > 160$ MeV already constrained by χ_B^6 for $\mu_B/T \leq 2 \rightarrow$ input for hydrodynamic modeling of QGP.

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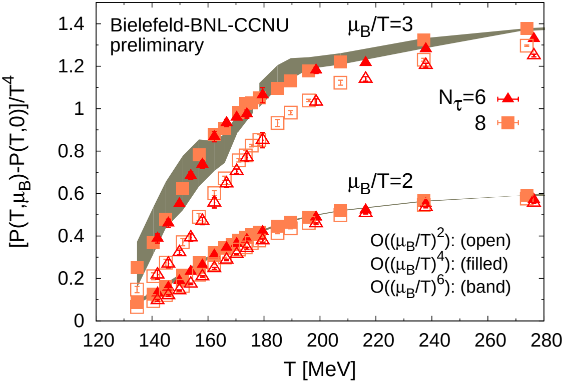
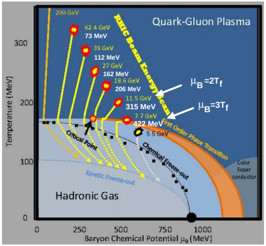
- Extension to $\mu_B/T \sim 3$ is in progress.





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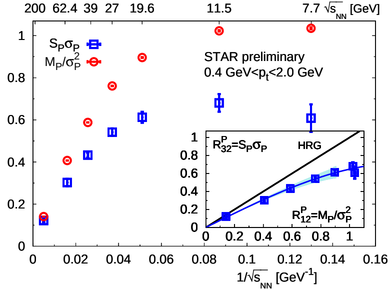
The fluctuations near T_c

$$\frac{P(T,\mu_B)-P(T,0)}{T^4}=\frac{\chi_2^B}{2}\left(\frac{\mu_B}{T}\right)^2\left[1+\frac{1}{12}\frac{\chi_2^B}{\chi_4^B}\left(\frac{\mu_B}{T}\right)^2+\ldots\right].$$



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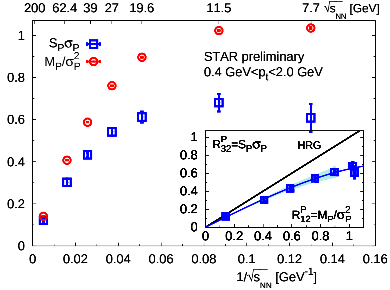

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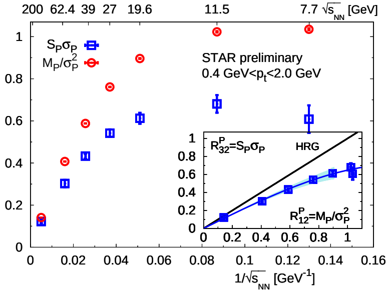

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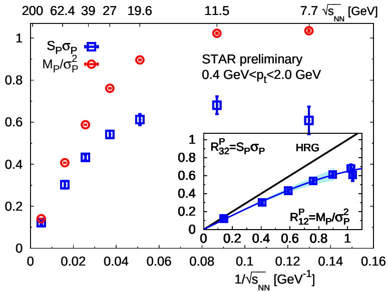

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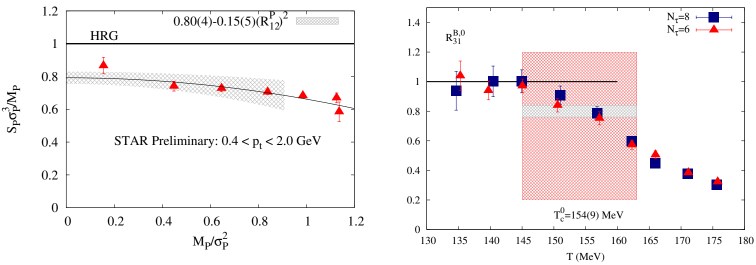
  By construction independent of μ_B.
- Strangeness neutrality condition: $\frac{n_p}{n_p+n_n}=0.4$.

Is this deviation consistent with the trend from Lattice?

$$\frac{S_B\sigma_B^3}{M_B} = \frac{\chi_2^B}{\chi_4^B} + \frac{1}{6}\left[\frac{\chi_6^B}{\chi_2^B} - \left(\frac{\chi_2^B}{\chi_4^B}\right)^2\right]\left(\frac{M_B}{\sigma_B^2}\right)^2 .$$

$$R_{31}^B = R_{31}^{B,0} + R_{31}^{B,2}\left(\frac{M_B}{\sigma_B^2}\right)^2 .$$ [Karsch et. al., arxiv:1512.06987]

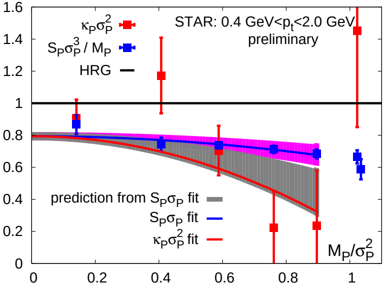
- Experimental data consistent with QCD prediction. Caveat $n_P \neq n_B$!



More Observables?

$$\textit{NLO} \quad \kappa_B\sigma_B^2 \text{ for } \mu_Q \sim \mu_S \sim 0: \qquad R_{42}^{B,2} = \frac{1}{2}\left[\frac{\chi_6^B}{\chi_2^B} - \left(\frac{\chi_2^B}{\chi_4^B}\right)^2\right] = 3R_{31}^{B,2}.$$

- Fit to experimental data shows these quantities are closely related.
- $R_{31}^{B,0} \approx R_{42}^{B,0}$. At NLO consistent within large errors in the data. [Bielefeld-BNL-CCNU collaboration, In preparation, 16]



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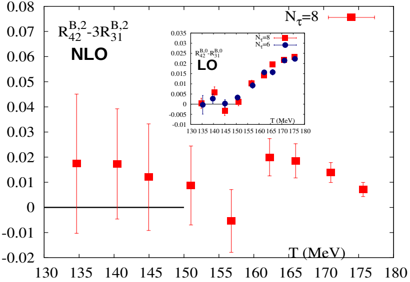

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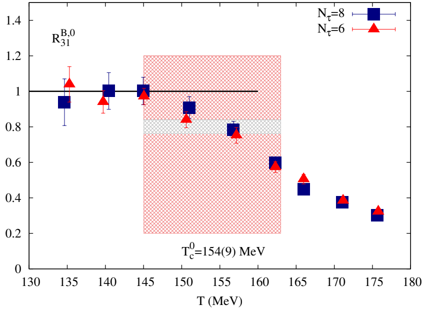
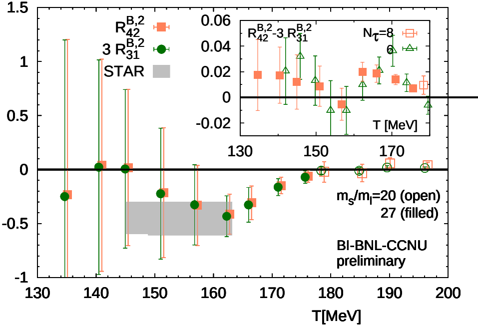
- The errors for $R_{31}^{B,2}$ not completely under control. Fit to the data consistent with LQCD predictions at present.





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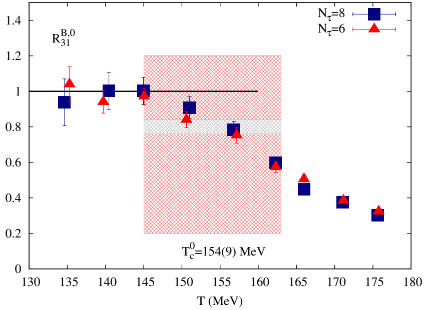
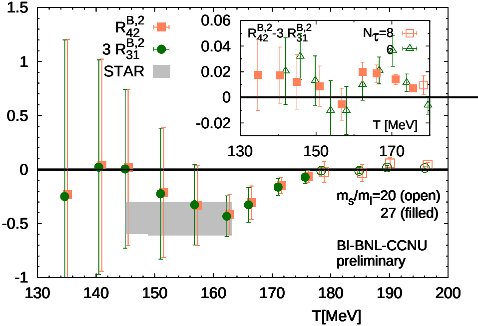
- Aiming for a factor two reduction of errors on 6th order cumulants near T_c.





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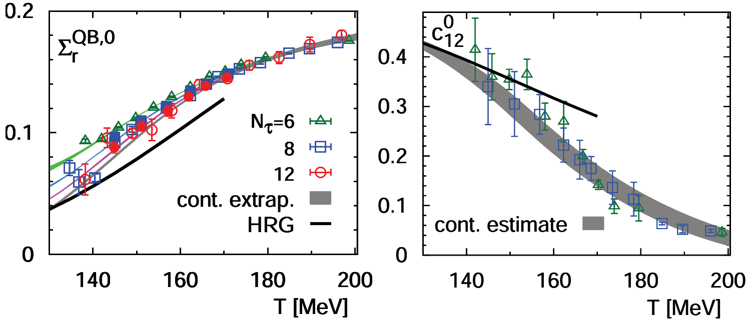
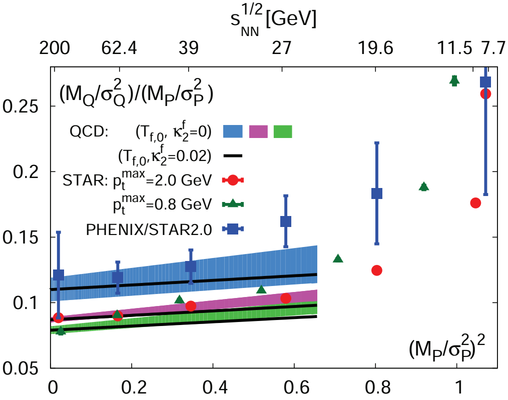
- As a result $\Sigma_r^{QB}(\mu_B) = \Sigma_r^{QB}(0) \left[1 + c_{12} \; \left(R_{12}^B\right)^2\right] + \mathcal{O}\left(R_{12}^B\right)^4$.
- An estimate of Σ_r^{QB} and R_{12}^B from experiments allows us to calculate c_{12}. [Bielefeld-BNL-CCNU collaboration, 15]

- Caveat: In experiments one measures protons Σ_r^{Qp}, R_{12}^p. Need to understand proton vs baryon number distributions. [Asakawa & Kitazawa, 12]. Within HRG at least R_{12}^B is mimicked by R_{12}^P within 10%.
- Additionally take into account also corrections due to finite range of momenta of detected particles.

  [Karsch, Morita and Redlich, 15, P Garg et. al., 13, Bzdak & Koch, 12].
- From the 2 independent expressions of Σ_r^{QB} we extract $c_{12}(T_{f,0}, \kappa_2^f) = c_{12}(T_{f,0}) - \kappa_2^f D_{12}$.

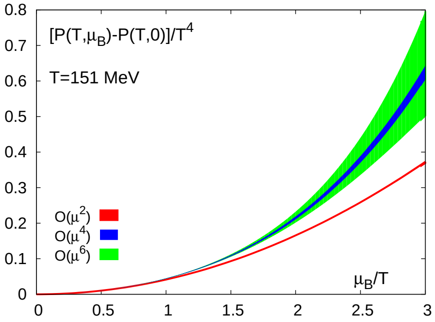




- This excercise give $T_{f,0} = 147$ MeV consistent with expectation that its at or below T_c.
  Curvature: $\kappa_2^f < -0.012(15) \rightarrow$ near to chiral curvature $\kappa_2^B = 0.0066(7)$.
  [Bielefeld-BNL-CCNU collaboration, 15]

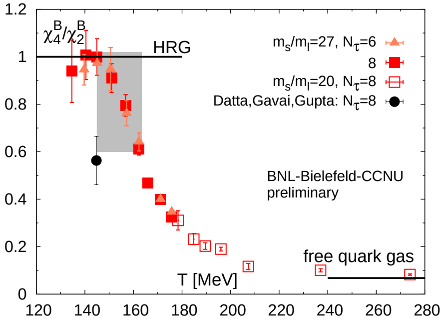
Breakdown of HRG

- Breakdown of HRG+ onset of criticality can be already constrained with χ_6^B.
- Near critical point all terms in the Taylor expansion nearly equal $\rightarrow$ need to improve the errors to observe!
- At CEP: $\chi_n > 0$, $\kappa_B \sigma_B^2 > 1$



- Radius of convergence: $r_{2n} \equiv \sqrt{2n(2n-1)\left|\frac{\chi^B_{2n}}{\chi^B_{2n+2}}\right|}$.
- Only existing result $T_{CEP} = 0.94\, T_c$ $\mu/T = 1.68(5)$

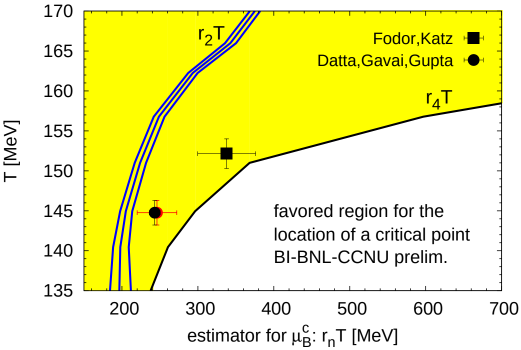
  [S.Datta, R. Gavai, S.Gupta, 13, Mumbai group]
- Lowest $r_{n=2}$ varies significantly from our estimates and HRG $\rightarrow$ lattice cut-off effects needs to be considered!

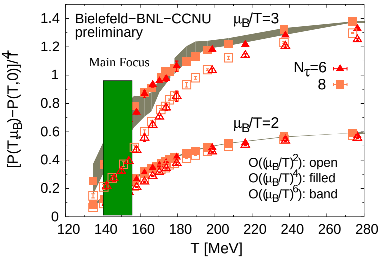


Critical-end point search from Lattice

- Current errors on our χ_6^B/χ_4^B only allow us to define a favored region for CEP!
- χ_8^B measured to get errors bounds on radius of convergence estimates.
- Connection to experiments non-trivial due to non-equilibrium effects.

  [S. Mukherjee, Y. Yin, R. Venugopalan, 15]





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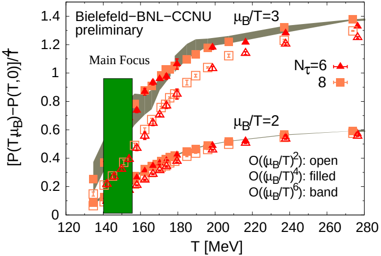
Outlook



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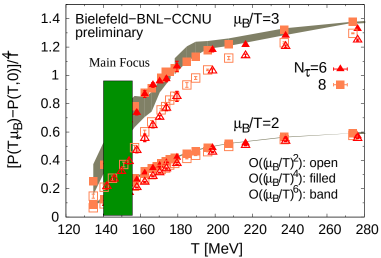

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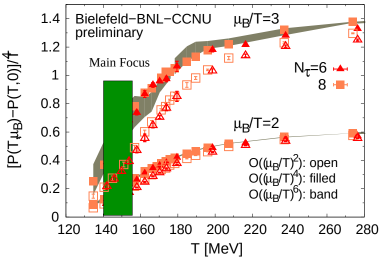

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- Analysis of χ_8^B ongoing. Crucial to estimate the errors on the EoS measured with the sixth order cumulants.
- Higher order cumulants will also help in bracketing the possible CEP. Current LQCD data suggest it is $\mu_B/T \leq 2$ but a larger value cannot be ruled out.